

# Feshbach Resonances in Fermionic ${}^6\text{Li}$

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Feshbach resonances in  ${}^6\text{Li}$  were experimentally studied and theoretically analyzed. In addition to two previously known  $s$ -wave resonances, we found three  $p$ -wave resonances. Four of these resonances are narrow and yield a precise value of the singlet scattering length, but do not allow us to accurately predict the location of the broad resonance near 83 mT. Its position was previously measured in a molecule-dissociation experiment for which we, here, discuss systematic shifts.

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Interactions in ultracold atomic gases can be magnetically tuned using Feshbach resonances. A Feshbach resonance occurs when the energy of two colliding atoms is nearly degenerate to the energy of a bound molecular state. Tunable interactions have been used to explore novel phenomena in collisional and many-body physics. Recently, Feshbach resonances have been used to control pairing processes in ultracold fermionic gases. This led to the observation of molecular Bose-Einstein condensates in  ${}^6\text{Li}$  [1, 2, 3, 4] and  ${}^{40}\text{K}$  [5], and to the first studies of the BEC-BCS crossover, the continuous transition of fermion pairs from weakly bound molecules to long range Cooper pairs [2, 4, 6, 7, 8, 9, 10].

In  ${}^6\text{Li}$  these experiments have been carried out in the vicinity of the  $s$ -wave Feshbach resonance near 830 G [2, 4, 7, 8, 9, 10] ( $1\text{ G} = 10^{-4}\text{ Tesla}$ ). The quantitative interpretation of these experiments and the characterization of the BEC-BCS crossover require a precise knowledge of the resonance location. However, its determination is not trivial since the resonance width is extremely large (180 G), and the line shape is strongly affected by many body effects. In our previous work we determined the position of this resonance by the onset of molecule dissociation to be  $822 \pm 3\text{ G}$  [7].

In this paper we report on a detailed study of Feshbach resonances in  ${}^6\text{Li}$  with the goal of accurately characterizing the interaction potential of two  ${}^6\text{Li}$  atoms. Three resonances in the  $|1\rangle$  and  $|2\rangle$  states which are  $p$ -wave resonances have been observed [11]. The positions of these Feshbach resonances together with the location of a narrow  $s$ -wave resonance in the  $|1\rangle + |2\rangle$  mixture near 543 G are used for a precise determination of the singlet  $s$ -wave scattering length. These results, however, do not constrain the position of the broad resonance, which also depends on the triplet scattering length. An improved measurement of its location is presented and the magnitude and the origin of possible systematic errors are discussed.

The experimental setup has been described in Ref. [12].

Up to  $4 \times 10^7$  quantum degenerate  ${}^6\text{Li}$  atoms in the  $|F, m_F\rangle = |3/2, 3/2\rangle$  state were obtained in a magnetic trap by sympathetic cooling with  ${}^{23}\text{Na}$ . The  ${}^6\text{Li}$  atoms were then transferred into an optical dipole trap (ODT) formed by a 1064 nm laser beam with a maximum power of 9 W. In the optical trap three different samples were prepared: A single radio-frequency sweep transferred the atoms to state  $|1\rangle$  ( $|F, m_F\rangle = |1/2, 1/2\rangle$  at low field). Another Landau-Zener sweep at an externally applied magnetic field of 565 G could then be used to either prepare the entire sample in state  $|2\rangle$  ( $|1/2, -1/2\rangle$  at low field) or create an equal mixture of atoms in state  $|1\rangle$  and  $|2\rangle$ . Except for the measurement of the broad  $s$ -wave Feshbach resonance, all resonances were observed by monitoring magnetic field dependent atom losses. Atom numbers were obtained from absorption images taken at zero field. The externally applied field was calibrated by driving microwave transitions from state  $|2\rangle$  to state  $|5\rangle$  ( $|3/2, 1/2\rangle$  at low field) and from state  $|1\rangle$  to state  $|6\rangle$  ( $|3/2, 3/2\rangle$  at low field) for several magnetic fields close to the resonance positions.

For spin polarized samples either in state  $|1\rangle$  or  $|2\rangle$   $s$ -wave scattering is forbidden by symmetry, therefore the observed resonances occur in the  $p$ -wave channel. The same molecular state that is responsible for these two resonances also causes a  $p$ -wave resonance in the  $|1\rangle + |2\rangle$  mixture.

The three  $p$ -wave resonances were observed in clouds with typical temperatures  $T$  of  $6\text{ }\mu\text{K}$ . This corresponds to  $T/T_F$  in the range of 0.5 to 1.5, where  $T_F$  is the Fermi temperature. Radial and axial trap frequencies were typically  $\omega_r = 2\pi \times 1.0\text{ kHz}$  and  $\omega_a = 2\pi \times 6.9\text{ Hz}$ .

The position of the  $p$ -wave resonance in the collision of a pair of state  $|1\rangle$  atoms was determined by first increasing the magnetic field in 300 ms to approximately 5 G below the resonance. Using an additional power supply to change the magnetic field within a 10 G range, the field was then switched in 1 ms to a test value  $B_{\text{test}}$ . Here the atoms were kept for 200 ms before the field and the

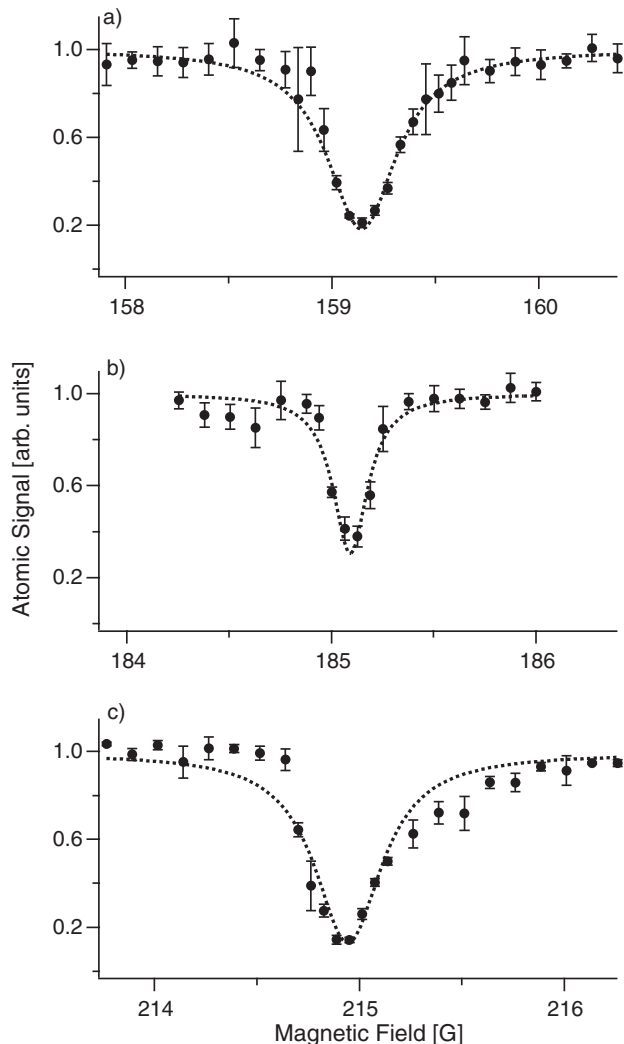


FIG. 1:  $P$ -wave resonances for  $|1\rangle + |1\rangle$  (a),  $|1\rangle + |2\rangle$  (b), and  $|2\rangle + |2\rangle$  (c) collisions. The resonances were fitted by a Lorentzian. The results are summarized in Table I.

optical trap were switched off. Finally atom number versus  $B_{\text{test}}$  was recorded. Resonantly enhanced losses due to inelastic three-body decay led to a Lorentzian shaped feature as shown in Fig. 1(a). Resonance positions and widths are summarized in Table I.

The same technique was used to measure the  $|1\rangle + |2\rangle$  and  $|2\rangle + |2\rangle$ ,  $p$ -wave resonances. The observed resonance lineshapes (see Fig. 1) are non-symmetric, possibly due to losses while switching the magnetic field to  $B_{\text{test}}$ , or due to evaporative cooling which was observed at magnetic fields  $B_{\text{test}}$  above the  $|1\rangle + |1\rangle$  and  $|2\rangle + |2\rangle$  resonances.

The  $s$ -wave resonance near 543 G in the  $|1\rangle + |2\rangle$  mixture was first observed in [13] and calculated in [14]. Its position was determined as presented above in clouds with typical temperatures of 6  $\mu\text{K}$ , but in a slightly

States	$B_{\text{exp}}$ [G]	$B_{\text{theory}}$ [G]	Width [G]
$ 1\rangle +  1\rangle$	$159.14 \pm 0.14$	159.15(4)	0.4
$ 1\rangle +  2\rangle$	$185.09 \pm 0.08$	185.15(4)	0.2
$ 2\rangle +  2\rangle$	$214.94 \pm 0.08$	214.90(4)	0.4
$ 1\rangle +  2\rangle$	$543.28 \pm 0.08$	543.27(5)	0.4
$ 1\rangle +  2\rangle$	822...834		

TABLE I: Position of the Feshbach resonances. Given are the experimentally and theoretically determined resonance locations  $B_{\text{exp}}$  and  $B_{\text{theory}}$  respectively, and the measured resonance width. The uncertainties for the experimental data in the first four rows are dominated by magnetic field drifts between the measurement of the resonance and the field calibration for which we measure an upper bound of 80 mG. For the  $|1\rangle + |1\rangle$  resonance an additional drift was monitored. The statistical error of determining the line center, and the estimated uncertainty due to asymmetric line shapes are negligible. For the broad  $s$ -wave resonance (fifth row) only a range is given. See the text for a discussion.

deeper optical trap and with an extended holdtime of 2900 ms at  $B_{\text{test}}$ . The result of a fit to the Lorentzian lineshape is given in Table I.

To determine the position of the broad Feshbach resonance near 830 G a different method was required. The resonance was identified as the onset of molecular dissociation [6, 7, 15]. Molecules were first created on the repulsive (BEC) side of the Feshbach resonance and then dissociated into atoms when the magnetic field crossed the resonance.

An almost pure  $^6\text{Li}_2$  molecular BEC at a magnetic field of about 780 G was prepared in the optical trap as described in Ref. [7]. The final ODT power was 36 mW, yielding trap frequencies of  $\omega = 2\pi \times 690$  Hz radially and  $\omega = 2\pi \times 12.5$  Hz axially. The axial frequency has a contribution from magnetic field curvature. After releasing the molecules from the optical trap, the magnetic field was held at 780 G for 2 ms, before it was ramped to a test value  $B_{\text{test}}$  in 14 ms. In these first 16 ms time of flight the molecular peak density dropped to  $n_{\text{mol}} = 5 \times 10^9 \text{ cm}^{-3}$ . The magnetic field was held at  $B_{\text{test}}$  for another 5 ms before it was switched off in two steps: at a initial speed of 100 G/ms for 2 ms to leave the resonance region and then at a faster speed (an exponential decay with initial time constant 30 G/ $\mu\text{s}$ ) to zero field in 3 ms. Finally the sample was imaged with light which was resonant only to atoms as the molecules are detuned by about -1.3 GHz from the atomic transition at zero field. By monitoring the atom number as a function of  $B_{\text{test}}$  the onset of molecule dissociation was observed at  $821 \pm 1$  G (Fig. 2).

There are at least two sources of systematic error to be considered. First, few-body collisions might dissociate molecules when their size, which near resonance is

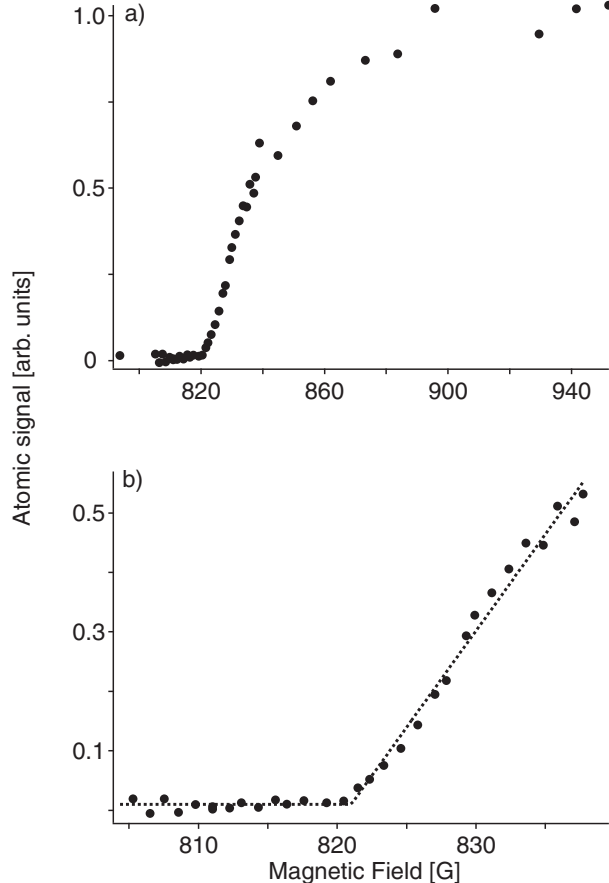


FIG. 2: Determination of the position of the broad  $s$ -wave Feshbach resonance. (a) Onset of dissociation of molecules into atoms at  $821 \pm 1$  G. (b) The resonance position was obtained by fitting two lines to the data points near the threshold, one horizontal through the points showing no atomic signal and a second line following the initial rise in atom number. The crossing of those two lines gave the resonance position, the estimated uncertainty in the crossing the quoted error of  $\pm 1$  G.

on the order of the scattering length between the constituent atoms [16], becomes comparable to the mean distance between the molecules. The scattering length near resonance is parameterized by  $a = a_{\text{bg}}(1 + \frac{\Delta B}{(B-B_0)}) \approx a_{\text{bg}} \frac{\Delta B}{(B-B_0)}$ , where  $a_{\text{bg}}$  is the negative background scattering length,  $B_0$  is the resonance position, and  $\Delta B$  is the resonance width. Molecule dissociation will become important at a magnetic field  $B$  at which  $a_{\text{bg}} \frac{\Delta B}{(B-B_0)} \sim n_{\text{mol}}^{-\frac{1}{3}}$  and the scattering length is positive. For our broad resonance this density-dependent few-body effect is expected to shift the resonance position to lower magnetic fields.

The second systematic error is a density independent, single molecule effect. Switching off the magnetic-field becomes non-adiabatic close to resonance and destroys

very-weakly bound molecules [17]. If  $\dot{\omega}/\omega^2$ , where  $\hbar\omega = \hbar^2/(ma^2)$  is the molecular binding energy and  $m$  is the atomic mass, becomes larger than unity, molecules are forced to change their size too fast and may dissociate. This systematically shifts the observed resonance position to lower magnetic fields. The shift due to this ramp-induced dissociation scales with  $B-B_0 \sim \dot{B}^{\frac{1}{3}}$ , where  $\dot{B}$  is the rate at which the magnetic field is initially switched off and  $B$  determines the magnetic field where molecule dissociation due to nonadiabaticity becomes important.

To determine the order of magnitude of these shifts we have measured the resonance locations for three different ramp rates at constant density and for three different densities at constant ramp rate.

At a molecular density of  $n_{\text{mol}} = 1.5 \times 10^{10}$  the resonance locations were measured at initial ramp speeds of 30 G/ $\mu\text{s}$  (fastest possible switch off), 100 G/ms (fastest externally controlled ramp), and 12.5 G/ms (controlled ramp). For the switch off the onset of dissociation occurs at  $793 \pm 7$  G, for the other two controlled ramps at  $822 \pm 3$  G and no relative shift is found within the errors. Assuming that no density shifts affect these data, one can extrapolate to zero ramp speed based on the  $(B-B_0) \propto \dot{B}^{\frac{1}{3}}$  dependence. In this way we find a resonance position of  $825 \pm 3$  G.

For a fixed initial ramp speed of 100 G/ms the resonance locations were determined at densities of  $5 \times 10^9$   $\text{cm}^{-3}$ ,  $1.5 \times 10^{10}$   $\text{cm}^{-3}$  and  $1.2 \times 10^{12}$   $\text{cm}^{-3}$  to be  $821 \pm 1$  G,  $822 \pm 3$  G and  $800 \pm 8$  G respectively [18]. Here one can use the  $(B-B_0) \propto n^{1/3}$  dependence to extrapolate to a resonance position of  $825 \pm 3$  G, neglecting effects due to nonadiabatic magnetic field ramps.

Both systematic effects shift the maximum magnetic field value at which the molecules are stable to lower magnetic fields. In a simple picture, one would expect the total shift to be the larger of the two. However, if they are similar, as in our case, they may add up or combine in a more complicated way. We have measured the threshold position at low density and slow ramp rates to be  $822 \pm 3$  G and determined two shifts of  $3 \pm 3$  G. Therefore, we expect the position of the Feshbach resonance to be between 822 and 834 G. A more accurate extrapolation requires measuring the dissociation threshold for more ramp speeds and densities. However, technical limitations in varying magnetic field ramp speeds and an unfavorable signal to noise ratio at lower densities precluded this.

All Feshbach resonances discussed in this paper are due to the  $v = 38$  vibrational state of the singlet potential with total electronic spin  $S$  equal to zero. The  $p$ -wave resonances have a total nuclear spin  $I$  equal to one, while the 543 G and broad  $s$ -wave resonances have  $I = 2$  and  $I = 0$ , respectively.

The resonance locations are compared with results of scattering coupled-channel calculations. We locate the resonance from the maximum of the elastic cross section

as a function of magnetic field. The collision energy is fixed at  $E = k_B T$ , where  $k_B$  is the Boltzmann constant and  $T$  is the experimental temperature. Our collision model, described in detail in Ref. [14], treats the singlet and triplet scattering length as adjustable parameters. The triplet state has a total electron spin equal to one. It turns out that all narrow resonances, which could be accurately located, are insensitive to the triplet scattering length. Only  $s$  and  $p$ -waves are included in the calculation. Fitting the singlet scattering length  $a_S$  to the field locations given in the first four rows of Table I yields a very accurate value of  $a_S = 45.1591(16) a_0$ , where  $a_0 = 0.0529177$  nm. With this value, the resonance positions given in the third column of Table I were calculated at a collision energy equal to  $k_B T$ . The agreement with the experimental values is excellent. The  $s$ -wave resonance is also in very good agreement with the determination of Ref. [19], 543.26(10) G. Our theoretical uncertainties do not include contributions due to a thermal average with respect to the collision energy. Moreover, the shift between the field values, at which the observed three-body loss rate and the theoretical two-body elastic cross section are maximal, is expected to be small but can not be ruled out at the current level of accuracy.

The broad resonance is caused by a hyperfine-induced mixing between a singlet vibrational level and an almost-bound virtual state of the triplet potential, a situation analyzed in [20, 21]. It is the virtual state that gives rise to the large and negative triplet scattering length  $a_T$  of  $^6\text{Li}$ . Mixing occurs for magnetic field values above 500 G. In fact, in absence of the hyperfine mixing the resonance would occur around 550 G. The coupling shifts the resonance by a few hundred Gauss. For typical Feshbach resonances, these shifts are no more than a few Gauss. A consequence of the large shift is that the resonance location depends critically on the less well known triplet potential.

In conclusion, we have found three  $p$ -wave Feshbach resonances in  $^6\text{Li}$ . They confirm the value of the singlet scattering length determined from the narrow  $s$ -wave resonance of Ref. [19]. The position of the broad resonances could not be constrained using the refined singlet potential. The determination of the position of the broad resonance via molecule dissociation is subject to systematic errors, which shift the onset of dissociation to lower magnetic fields.

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